The Utilization of Electrochromic Materials for Smart Window Applications in Energy-Efficient Buildings

Bjørn Petter Jelle [ab]* and Tao Gao [c]

[a] SINTEF Building and Infrastructure,
Department of Materials and Structures, NO-7465 Trondheim, Norway.
[b] Norwegian University of Science and Technology (NTNU),
Department of Civil and Transport Engineering, NO-7491 Trondheim, Norway.
[c] Norwegian University of Science and Technology (NTNU),
Department of Architectural Design, History and Technology, NO-7491 Trondheim, Norway.
* Corresponding author: bjorn.petter.jelle@sintef.no (e-mail), +47-73593377 (phone).

ABSTRACT

Electrochromic materials (ECM) and windows (ECW) are able to regulate the solar radiation throughput by application of an external electrical voltage. Thus, ECWs may decrease heating, cooling, lighting and electricity loads in buildings by admitting the optimum level of solar energy and daylight at any given time, e.g. cold winter climate versus warm summer climate demands. It is crucial to be able to compare the dynamic solar radiation control for different ECWs and hence require specific ECW properties. The solar radiation control for ECWs may readily be characterized by several solar radiation glazing factors, where a comparison for various ECW configurations enables one to select the most appropriate ones for specific smart window applications in energy-efficient buildings. As an example a particular ECW based on the ECMs polyaniline, prussian blue and tungsten oxide is presented, being able to regulate as much as 60 % of the visible and 59 % of the total solar radiation.

Keywords: electrochromic, material, smart window, solar radiation, energy-efficient.

1 INTRODUCTION

Electrochromic materials (ECM) in electrochromic windows (ECW) aim at controlling the solar radiation throughput at the earth's surface, which is roughly located between 300 nm and 3000 nm. Such windows are also often denoted smart windows. The ECW solar control is achieved by application of an external voltage. The visible (VIS) light lies between 380 and 780 nm. Ultraviolet (UV) and near infrared (NIR) radiation are located below and above the VIS region, respectively. Above 3000 nm, and not part of the direct solar radiation, lies the thermal radiation called infrared (IR) radiation, which all materials radiate above absolute zero, i.e. above 0 K, peaking around 10 000 nm (10 μm) at room temperature. However, the ECWs are not aimed at controlling the IR radiation. Normally, as low as possible heat loss through windows is desired, i.e. low U-value, which is accomplished by the application of various static low emissivity coatings on the window glass panes. Miscellaneous ECMs and ECWs and their various properties are investigated in the literature [1-10]. Some commercial ECWs are also already on the market [8,9]. ECMs and ECWs may also be used together with other materials and technologies, e.g. self-cleaning glazing materials and building integrated photovoltaics (BIPV) like solar cell glazing [11-15]. In general, it is of major importance to investigate the durability of building materials and components, also newly developed ones like e.g. ECMs and ECWs, which may be performed by carrying out accelerated climate ageing in the laboratory [16]. Thus, conducting a robustness assessment of these materials and components may also be beneficial [17]. Hence, a durability and robustness evaluation of the new ECMs and ECWs should be carried out. This work presents a specific ECW and corresponding characterization by solar radiation glazing factors, i.e. ultraviolet solar transmittance (T_{uv}), visible solar transmittance (T_{vis}), solar transmittance (T_{sol}), solar material protection factor (SMPF), solar skin protection factor (SSPF), external visible solar reflectance ($R_{vis,ext}$), internal visible solar reflectance ($R_{vis,int}$), solar reflectance (R_{sol}), solar absorbance (A_{sol}), emissivity (ε), solar factor (SF) and colour rendering factor (CRF). The solar factor (SF), which is the total solar energy transmittance, is also often denoted as the solar heat gain coefficient (SHGC) and the g-value. Further details about the solar radiation glazing factors are given in the literature [10,18,19].

2 EXPERIMENTAL

Experimental details concerning the synthesis and manufacturing of ECMs and complete ECWs, and their electrochemical and spectroscopical characterization, are described in the studies by Jelle [10], Jelle and Hagen [20-

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22] and Jelle et al. [23]. In short, the ECMs polyaniline (PANI), prussian blue (PB) and tungsten oxide (WO_3) were deposited electrochemically onto transparent conducting glass plates coated with indium-tin-oxide (ITO), i.e. indium oxide doped with tin ($In_2O_3(Sn)$), whereas solid state ECWs were then constructed by applying the solid state polymer electrolyte poly(2-acrylamido-2-methyl-propane-sulphonic acid) (PAMPS) as an ionic conductor, see Fig.1 for a schematic drawing of the ECW presented here.

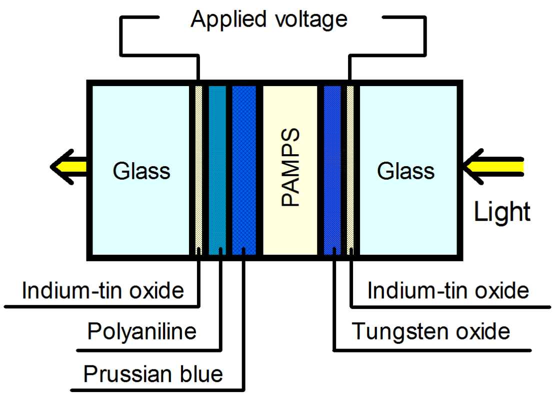

Figure 1: Schematic drawing of the ECW configuration based on the ECMs polyaniline (PANI), prussian blue (PB) and tungsten oxide (WO_3).

A Cary 5 UV-VIS-NIR spectrophotometer, with an absolute reflectance accessory (Strong-type, VW principle), was used to measure the transmittance and reflectance of the ECWs, whereas emissivity measurements were performed with a SOC-100 HDR Hemispherical Directional Reflectometer from Surface Optics Corporation connected to a Thermo Nicolet 8700 Fourier transform infrared (FTIR) Spectrometer.

3 RESULTS AND DISCUSSION

Measured transmittance spectra for an ECW at various applied electrical potentials (voltages) are given in Fig.2, with corresponding calculated solar radiation glazing factors and factor modulations in Table 1 and Table 2, respectively, for the lowest and highest electrical potential.

As to show an example of the calculation procedure for the solar radiation glazing factors, the solar transmittance (T_{sol}) is given by the following expression [9]:

$$T_{sol} = \frac{\sum_{\lambda=300nm}^{2500nm} T(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=300nm}^{2500nm} S_\lambda \Delta\lambda} \quad (1)$$

where S_λ is the relative spectral distribution of solar radiation, $T(\lambda)$ is the spectral transmittance of the glass, λ is the wavelength, $\Delta\lambda$ is the wavelength interval, and the $S_\lambda\Delta\lambda$ values at different wavelengths are given as tabulated values [10,18].

The T_{sol} value will thus be a number between 0 and 1 (or 0 and 100 %), calculated in the main part of the solar spectrum, i.e. 300-2500 nm. A low number indicates a low transmission of solar radiation, whereas a high number represents a high solar radiation transmission. Note that the whole solar spectrum is not covered in the (standard) calculation of T_{sol}, and in future versions the wavelength range may favourably be extended to cover an even larger part of the solar radiation, e.g. from 290 nm to 3000 nm.

In similar ways the other solar radiation glazing factors may be calculated, except the ε, SF and CRF values which follow other calculation procedures [10,18]. The ECW modulation level given in Table 2 is calculated by subtracting the solar radiation glazing factors for the same ECW at the high and low potentials given in Table 1, e.g. as for ΔT_{sol}:

$$\Delta T_{sol} = T_{sol}(\text{bleached}) - T_{sol}(\text{coloured}) \quad (2)$$

where the T_{sol} values in Table 1 are calculated from Eq.1 and likewise for the other solar radiation glazing factors.

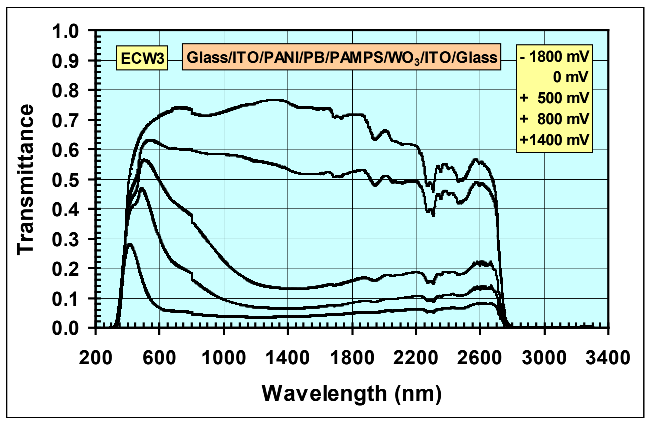

Figure 2: Transmittance vs. wavelength in the whole solar spectrum measured for an ECW at various applied potentials [10,21,23]. Highest colouration level is at +1400 mV.

It is observed from Table 1 that various solar radiation glazing factors may obtain both high and low values depending upon the applied electrical potential in the ECW, e.g. changing the T_{vis} value from 0.69 to 0.09. It is also noted that this ECW contains solar radiation absorbing electrochromic materials, i.e. not reflecting materials, as the changes with applied potential occur in the transmittance (e.g. T_{sol}) and absorbance (e.g. A_{sol}) values, and not in the reflectance (e.g. R_{sol}) values.

As expected, the highest colouration level gives the largest SMPF values, i.e. the best protection of materials is achieved with the darkest ECW, e.g. compare a SMPF value of 0.83 in the coloured state with 0.59 in the transparent (bleached) state.

The CRF value of 0.96 in the transparent (bleached) state is very high, i.e. a very good colour rendering. However, in the coloured state, the CRF value is substantially reduced, i.e. CRF = 0.59.

Table 1: Calculated solar radiation glazing factors for an ECW at two colouration levels (transparent and dark coloured), i.e. at two applied potentials (e.g. Eq.1). Corresponding transmittance spectra are given in Fig.2.

Solar radiation glazing factor	-1800 mV	+1400 mV
T_{uv}	0.08	0.12
T_{vis}	0.69	0.09
T_{sol}	0.67	0.08
SMPF	0.59	0.83
SSPF	0.97	0.97
$R_{vis,ext}$	0.09	0.09
$R_{vis,int}$	0.09	0.09
R_{sol}	0.08	0.08
A_{sol}	0.25	0.84
ε	0.836	0.836
SF	0.74	0.30
CRF	0.96	0.59

Table 2: Calculated solar radiation glazing factor modulations for an ECW. The modulation level is calculated by subtracting the solar radiation glazing factors at the high and low potentials given in Table 1 (e.g. Eq.2).

Solar radiation glazing factor modulation	Modulation between -1800 mV and +1400 mV
ΔT_{uv}	-0.04
ΔT_{vis}	0.60
ΔT_{sol}	0.59
ΔSMPF	-0.24
ΔSSPF	0.00
$\Delta R_{vis,ext}$	0.00
$\Delta R_{vis,int}$	0.00
ΔR_{sol}	0.00
ΔA_{sol}	-0.59
$\Delta\varepsilon$	-
ΔSF	0.44
ΔCRF	0.37

The ECW device has a rather large solar radiation modulation ability, e.g. $\Delta T_{vis} = 0.60$ and $\Delta T_{sol} = 0.59$, where the transmittance modulation is assumed to be due to absorbance regulation, i.e. $\Delta A_{sol} = -0.59$.

Note that reflectance values of the ECW have not been measured, but as the (absorbing) electrochromic coatings are located between two glass plates, the (low) reflectance values will be close to the values for float glass, and these are hence employed in the current calculations.

Although the solar factor modulation is lower than the solar transmission counterpart for the ECW, the solar factor modulation is still quite high, i.e. ΔSF = 0.44. Hence, this ECW is able to regulate large parts of the solar radiation, and the regulation may be readily characterized by the solar radiation glazing factors. Applying the ECW into two-layer and three-layer window pane configurations reduces the total solar energy throughput modulation in the windows, which may also be seen in the ΔT_{sol} and ΔSF values, as several layers of glass and coatings will increase the total reflectance and absorbance (not depicted here, for examples it is referred to the study by Jelle [10]), i.e. less solar radiation left for the ECWs to modulate (regulate). That is, the solar radiation modulation by an ECW will decrease with the number of glass panes and low emittance coatings added to the total window configuration.

An interesting aspect is that the doping mechanisms in PANI include both redox processes and proton doping [2,24,25], and the characteristic absorbance shift from the NIR to the VIS region for PANI makes it appropriate to plot the absorbance versus both wavelength and applied electrical potential in order to enhance the visualization of the absorbance changes. Thus, a 3-dimensional graphical plot of light absorbance versus wavelength for PANI on ITO glass in an aqueous solution of 0.1 M $Na_2SO_4 \cdot 10H_2O$ and 0.001 M H_2SO_4 (pH 3.7) at different applied potentials versus Ag/AgCl (3.5 M KCl) is depicted in Fig.3 [2,10,22].

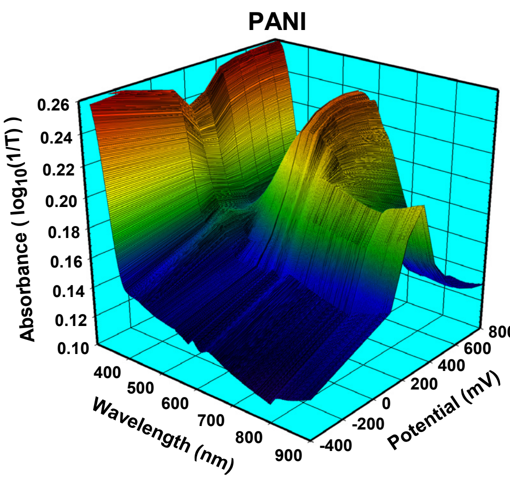

Figure 3: A 3-dimensional graphical plot of light absorbance versus wavelength for PANI on ITO glass in an aqueous solution at different applied potentials vs. Ag/AgCl (3.5 M KCl). The absorbance in the ITO glass, electrolyte and cell has been subtracted by the use of a reference cell in the double beam spectrophotometer [2,10,22].

4 CONCLUSIONS

A dynamical control of daylight and solar energy in buildings may be achieved by application of electrochromic windows (ECW). This control may be readily characterized by solar radiation glazing factors, i.e. ultraviolet solar transmittance, visible solar transmittance, solar transmittance, solar material protection factor, solar skin protection factor, external visible solar reflectance, internal visible solar reflectance, solar reflectance, solar absorbance, emissivity, solar factor and colour rendering factor. A specific ECW has been presented, demonstrating a large solar radiation modulation.

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